Experimental Simulation of Electrical Breakdown in Partially Enclosed Structures in the Space Environment

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Abstract

The use of high voltage systems in the space environment is characterized by extreme conditions such as non-uniform fields, $Nd/(Nd)_m << 1$, the presence of magnetic fields (geomagnetic or induced by current carrying structures) and the space plasma. This paper presents breakdown measurements in a simulated space environment. The experimental chamber, 2.34 m in diameter, 6.5 m long can be filled with a homogeneous plasma and atomic species of molecular gases. Breakdown experiments were performed with spherical anodes in different gases such as Argon, Nitrogen, air, and Oxygen, with and without plasma. The breakdown voltage is, at low pressures, a double-valued function of the B-field with a critical field below which no bulk breakdown occurs. Breakdown curves and critical B-fields versus pressure for different gases are presented.

Introduction

One important question in the design of space based high voltage systems is whether or not the space vacuum can be used as electric insulation. Especially under conditions of low earth orbits and close to components with high outgassing rates the possibility of breakdown has to be investigated. The operating conditions of high voltage systems in space is characterized by extreme conditions such as non-uniform fields with $Nd/(Nd)_m << 1$ (N: gas density; d: electrode separation; $(Nd)_m$ value of Nd at the Paschen minimum), the presence of magnetic fields (either geomagnetic or induced by current carrying structures) and the presence of the "space" plasma. Especially in crossed electric and magnetic fields trapped electron orbits can occur allowing collisional ionization in structures with dimensions smaller than the mean free path. The problem of electrical breakdown in open and partially enclosed structures under such extreme conditions has always been of great theoretical and technical interest for utilization of the space environment as a high voltage insulator and for developing design guidelines for high voltage systems in space.

In other papers presented at this conference we have theoretically investigated breakdown of the insulating properties of the space environment in enclosed [1] and open [2] structures. In this article we present experimental investigations of electrical breakdown under simulated space conditions in a vacuum chamber, for generic geometries. The experimental results can be used to validate models for breakdown under such extreme conditions.

Experimental Facility

The general setup of our Space Simulation Facility is shown in Fig. 1. The stainless steel tank was previously used as the expansion chamber of a shock tunnel. The main part of this tank is 2.34 m in diameter and 6.5 m long. At one end a 3.3 m long cone is attached. The chamber is evacuated by a 40 cm. diameter diffusion pump which can pump the system down to approximately $4 10^{-7}$ torr.

The cone is used to attach a plasma source. We use a cylindrical stainless steel hollow cathode with an inner diameter of 14.3 cm. and a length of 21 cm. The anode is an internal water cooled copper rod of 2.5 cm. outer diameter. The transition between hollow cathode and chamber is a nozzle with a diameter of 1.27 cm.

Specific gases can be fed into the system in different ways. One gas feed is into the hollow cathode. This is the gas in which the hollow cathode discharge operates and a plasma is generated that expands through the nozzle into the experimental chamber. The second gas feed is into the nozzle itself. This allows the hollow cathode to be operated in one gas and another gas to be added to the expanding plasma. Two grids with independent grid control voltage outside the nozzle allow controlling the ion and electron fluxes into the chamber. This allows in some limit to adjust the densities of different discharge products, such as dissociated and ion fed species independently. The operation of the hollow cathode requires a minimum gas flow into the hollow cathode. With helium, for example, the minimum chamber pressure with plasma generation in the hollow cathode chamber is ~ 1 torr.

The tank is equipped with a current-carrying coil to generate an axial magnetic field. Because of the different flanges the field coil is built in sections. The resulting field variations on the axis are smaller than 2% and at one half of the chamber radius approximately 3%. The field can be varied from zero (ambient earth magnetic field) up to ~ 14 Gauss. To assure a homogeneous fill of the chamber with plasma the B-field is significantly higher at the hollow cathode and is tapered along the cone so that the B-field lines at the wall are parallel to the wall.

Several flanges provide access for various experimental equipment and allow to simulate different geometries. Standard equipment includes pressure gauges, Langmuir probes, and axial and radial optical access for spectroscopic investigations. The geometry investigated at this time is that of a positive sphere in a cylinder. For this purpose the sphere is mounted on a bushing with potential grading calculated for this geometry. The mount of this bushing can be tilted such that the sphere can be moved in an off-center of the chamber to investigate the consequence of the asymmetry on the electron orbits.

Experimental Investigations

Breakdown experiments were performed in different gases such as Argon, Nitrogen, air and Oxygen, with and without the presence of a plasma. All measurements, at this time, are DC breakdown measurement in which either the voltage or the magnetic field has been slowly increased or decreased.

The first set of experiments involves the breakdown between an outer negative cylinder and a positive sphere on the cylinder axis without plasma. Similar measurements have been performed by Readhead [3], however in a much smaller chamber. These experiments therefore do not cover the full parameter range accessible with our chamber. Figure 2 shows the dependence of the breakdown voltage on the magnetic field with the gas density as the variable parameter. The gas was Argon. The breakdown voltage is, at low pressures, a double-valued function of the magnetic field with a critical magnetic field below which no bulk breakdown occurs [1,3,4]. The breakdown curves for Argon and air in the absence of plasma are similar. The lower branches of these curves were measured by increasing the voltage at constant magnetic fields while the upper branch was measured by increasing the magnetic field at constant voltage.

The branches of these breakdown curves are related to the cycloid type trajectories of the electrons in crossed electric and magnetic fields. At voltages below the lower branch the electrons do not gain sufficient energy for ionization within one cycloid while above the upper branch the cycloidal paths lead directly to the anode and no electron trapping occurs. At high densities the mean free path of the electrons becomes shorter than the dimension of the electrode separation and avalanching is possible without trapped orbits. For this condition the upper branch of the breakdown curve disappears [1].

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14. ABSTRACT

The use. of high voltage systems in the space environment is characterized by extreme conditions such as non-uniform fields, Nd/(Nd)m < < 1, the presence of magnetic fields (geomagnetic or induced by current carrying structures) and the space plasma. This paper presents breakdown measurements in a simulated space environment. The experimental chamber, 2.34 m in diameter, 6.5 m long can be filled with a homogeneous plasma and atomic species of molecular gases. Breakdown experiments were performed with spherical anodes in different gases such as Argon, Nitrogen, air, and Oxygen, with and without plasma. The breakdown voltage is, at low pressures, a double-valued function of the B-field with a critical field below which no bulk breakdown occurs. Breakdown curves and critical B-fields versus pressure for different gases are presented.

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The breakdown characterizes for low densities also show a critical magnetic field B_{crit} for a given gas density below which breakdown does not occur. Figure 3 shows the dependence of B_{crit} on the density of air for this geometry. This curve demonstrates the importance of the B-field which has to be large enough to generate trapped electron orbits with sufficient energy for ionization to cause breakdown.

A detailed discussion of the conditions for breakdown and the dependence of the two branches and the critical B-field on gas density and cathode and anode geometry is presented in a separate paper in these proceedings [1].

Figure 4 shows again the breakdown voltage versus magnetic field with the gas density as the variable parameter, this time for Nitrogen (N_2). At low densities we experience the same type of breakdown curves as for Argon and air with two branches and at high pressures avalanching occurs without the need of a B-field to generate trapped orbits. In the transition between the high and the low densities we experienced a discontinuity at low magnetic fields (Fig. 5). The specific behavior of breakdown in the transition between "high" and "low" density is not clear at this time.

The measurement of the breakdown voltage versus the gas density for B=0 generates the Paschen curve for this specific geometry. It should be mentioned, however, that the earth's magnetic field of approximately 0.5 Gauss was not compensated. This field is at an angle with respect to the cylinder axis. The error because of this earth's magnetic field can be considered to be small since the B-field dependence of the breakdown voltage at high densities is weak (Fig. 4).

Conclusions

We have measured the DC breakdown characteristic for the generic geometry of a positive sphere in a cylinder under the influence of a weak axial magnetic field. The main features of the breakdown characteristics provide guidelines for designing high voltage system in the space environment:

1. The dependence of the breakdown voltage on the magnetic field for low densities has two branches which merge at a critical value of the B-field, B_{crit}, below which no breakdown occurs. The regime in the V-B plane in which breakdown occurs generates trapped electron orbits with electron energies sufficient for ionization.
2. At voltages above the upper branch of the breakdown curve the electrons are forced into orbits which lead directly from the cathode to the anode so that no electron trapping is possible. This branch disappears at higher densities for which the mean free path is smaller than the interelectrode spacing.
3. At voltages below the lower branch of the breakdown curve the electrons do not gain sufficient energy for ionization within the cycloidal orbit. For high pressures and low B-fields this branch connects to the Townsend breakdown mechanism in which the energy gain is limited by collisions.

   Very high magnetic fields strongly limit the energy gain of the electrons and increase the breakdown voltage in the lower branch (magnetic insulation). The B-fields required for this condition are orders of magnitude higher than used in our experiments.
4. The critical magnetic field, B_{crit}, below which no breakdown occurs increases strongly with decreasing pressure. For increasing pressure the upper branch of the breakdown curve disappears and consequently a critical magnetic field does not exist above a critical gas density, N_{crit}. This critical gas density depends on the geometry and dimension of the electrodes.

References

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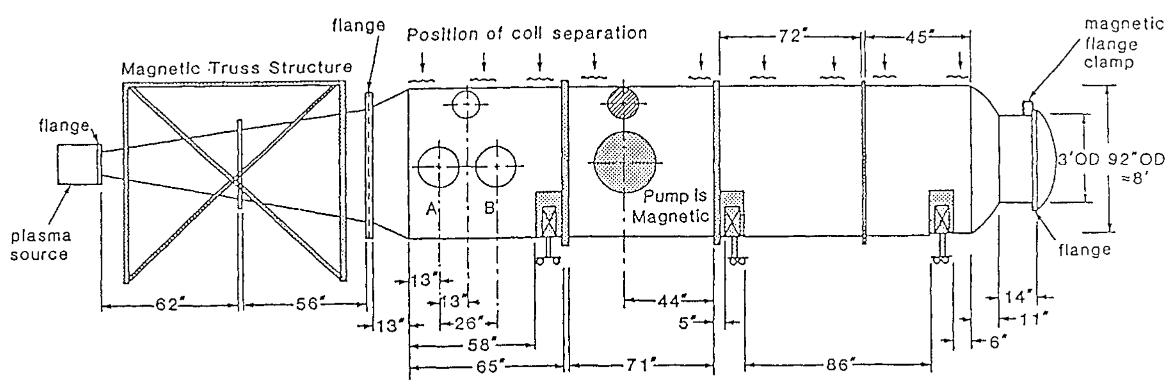

Fig. 1. Experimental setup of the space simulation facility.

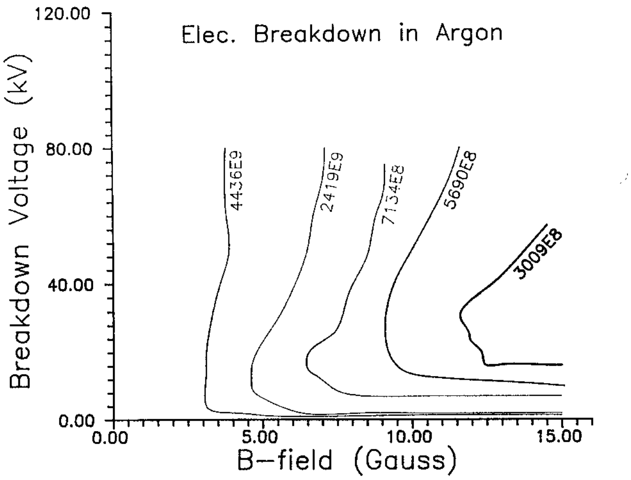

Fig. 2. Measured breakdown voltage versus magnetic field in Argon with the density as the variable parameter (r_s = 5.08 cm, r_c = 117 cm).

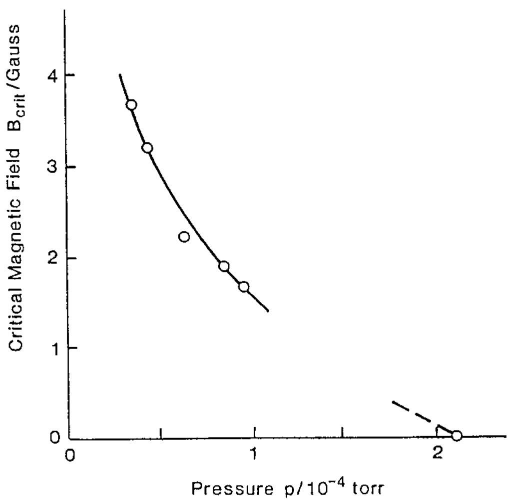

Fig. 3. Critical B-field versus gas density in air (r_a = 5.08 cm, r_c = 117 cm).

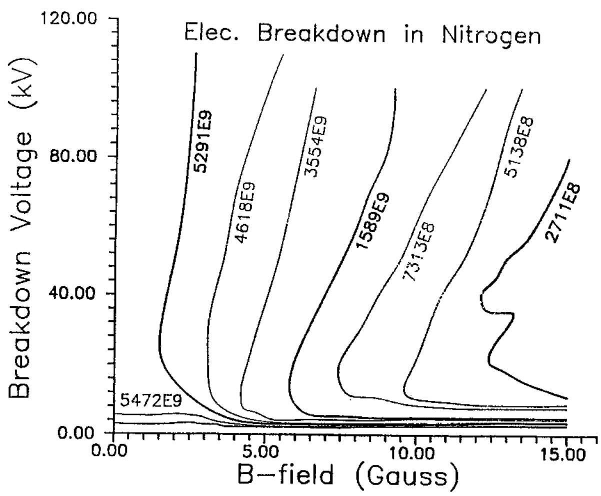

Fig. 4. Measured breakdown voltage versus mangetic field in Nitrogen with the density as the variable parameter (r_a = 5.08cm, r_c = 117cm).

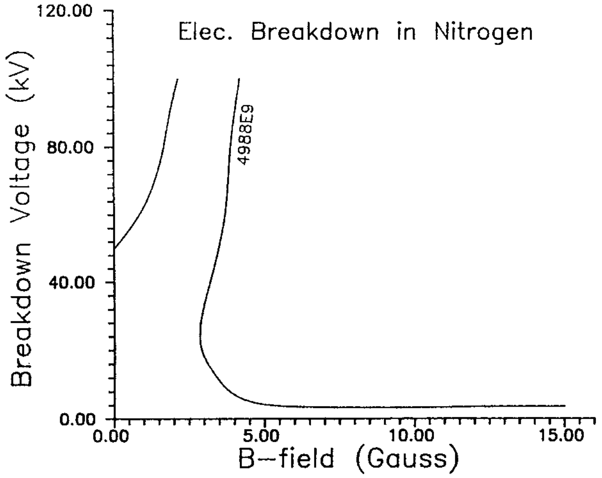

Fig. 5. Measured breakdown voltage versus magnetic field in Nitrogen in the density transitioin region.